METHOD AND APPARATUS FOR SHEAR PROPERTY CHARACTERIZATION FROM RESONANCE INDUCED BY OSCILLATORY RADIATION FORCE

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to provisional application Serial No. 60/461,605, filed April 9, 2004, incorporated by reference herein.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] This work was supported by grant HL61451 from the National Institutes of Health and grant DAMD 17-98-1-8121 from the Department of Defense.

BACKGROUND OF THE INVENTION

[0003] The present invention relates to a method and apparatus for determining shear elasticity and shear viscosity of a material, and more particularly to a method for determining the shear elasticity and shear viscosity of a material based on resonance spectra of the medium under test.

[0004] The study of objects in terms of their mechanical response to external forces is of considerable interest in material science and medical diagnosis. Changes of elasticity of soft tissues are often related to pathology, and therefore the study of and characterization of changes in elasticity of materials can be an important diagnostic tool.

[0005] Traditionally, the mechanical characteristics of tissue have been examined through palpation. Palpation is a process in which a static force is applied to tissue and an estimation of the tissue elasticity is made through the sense of touch. While providing some information regarding the characteristics of the tissue, this method is highly dependent on the opinion of the medical practitioner estimating the force, and, although often useful, is not repeatable and does not provide a useful scale for characterizing the tissue.

[0006] Another prior art method for characterizing the mechanical properties of tissue is elasticity imaging, which has been the subject of extensive investigation in recent years.

Elasticity imaging provides a quantitative method for measuring the mechanical properties of tissue. Generally, an excitation force is applied to the tissue and the response of the tissue is used to reconstruct the elastic parameters of the tissue. These parameters are typically related to the shear modulus, or "hardness" of the tissues being imaged. While providing a means for repeatably characterizing tissue, however, the ability of conventional B mode ultrasound imaging to differentiate various tissues depends principally on the acoustic impedance, which in turn depends upon the bulk modulus of the tissue under examination. The range of variation of bulk modulus, however, is relatively small. Therefore, the bulk modulus does not vary sufficiently as a function of the state of the tissue to allow for a characterization of the tissue.

[0007] Recently, vibro-acoustography, a method that can image the "hardness" of an object, has been developed. In vibro-acoustography, a confocal transducer having a center disk and an outer ring introduces two ultrasound beams to the same focal spot in an object. The two ultrasound beams have slightly different frequencies: for example, 1.001 MHz, and 0.999 MHz. At the focal spot, the interference of these two beams causes the object to vibrate at the beat frequency, in this example, at 2 kHz. Acoustic emissions from the object are detected by an acoustic hydrophone. These emissions contain information about the local material properties of the object.

[0008] By scanning the focal plane of the transducer in a raster manner, a 2D image of the object can be generated. In this method, the applied force is oscillative, allowing the dynamic properties of the material to be examined. The force is also confined to a local spot, therefore providing good spatial resolution of the image. This method is therefore particularly useful in detecting hard inclusions in soft material. For example, it has been used to image calcification in human arteries, microcalcification in breast tissue, and fractures in metal parts.

[0009] In vibro-acoustography, the brightness of a pixel is related to the stiffness and reflectivity of that location. However, the image is not a direct representation of a single elastic modulus. Rather, it combines information about several material properties of the object. Therefore, present versions of vibro-acoustography do not provide a direct evaluation of the stiffness of a material under examination.

SUMMARY OF THE INVENTION

[0010] The present invention is a method for characterizing an elasticity property of a viscous medium. A focused ultrasound wave is directed at the viscous medium to produce a vibrational force on the medium, and a vibrational velocity of the medium is determined as a function of the frequency of vibration. These steps are repeated over a range of frequencies to develop a velocity versus frequency spectrum of the medium. A resonant frequency is determined, and the resonant frequency and/or the resonant spectrum are used to determine an elasticity property of the medium, and can be used to determine or estimate at least one of a shear elasticity or a shear viscosity.

[0011] In another aspect of the invention, an apparatus for determining an elasticity property of a viscous medium is provided. The apparatus includes an ultrasound transducer for applying an ultrasound beam operating at a selectively varying frequency at the viscous medium, and a detector for measuring a velocity and a frequency of vibration of the medium as the ultrasound wave is applied. A processing unit is electrically connected to the transducer to drive the transducer to emit waves at varying frequencies over a selected frequency range, and to the detector to receive the velocity of vibration from the detector, the frequency and velocity providing coordinates for a resonance profile. Based on the resonance profile, the processing unit determines at least one of a shear elasticity and a shear viscosity. The transducer can be directed at various positions in the medium, and the shear elasticity

and shear viscosity determined at multiple locations in order to characterize variations in the medium.

[0012] These and other aspects of the invention will become apparent from the following description. In the description, reference is made to the accompanying drawings which form a part hereof, and in which there is shown a preferred embodiment of the invention. Such embodiment does not necessarily represent the full scope of the invention and reference is made therefore, to the claims herein for interpreting the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] Figure 1 is an illustration of an ultrasound transducer showing various coordinates.

[0014] Figure 2 is a chart illustrating velocity versus frequency resonance spectra for a computer simulation of a homogeneous medium having a fixed shear viscosity and varying shear elasticities.

[0015] Figure 3 is a chart illustrating velocity versus frequency resonance spectra for a computer simulation of a homogeneous medium having a fixed shear elasticity and varying shear elasticities.

[0016] Figure 4 is a block diagram of a system for performing the method of the invention.

[0017] Figure 5 is a velocity spectra illustrating resonance for homogeneous gels having varying degrees of stiffness.

[0018] Figure 6 is a block diagram of a second embodiment of a system for performing the method of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0019] The present invention comprises a method for characterizing material properties of a viscous medium as a function of a resonance of a velocity of vibration in the medium when subjected to an applied stimulating oscillatory force. A profile of vibration velocity versus frequency is developed, and the resonant frequency of the medium is evaluated. The derived profile and resonant frequency are used to characterize the shear properties of the viscous medium, including both shear modulus and shear viscosity. The range of values of the shear modulus and viscosity of a tissue is substantially greater than that of prior art methods which relied, for example, on bulk modular parameters, and therefore provide an improved diagnostic value over bulk modulus methods.

Theory

[0020] The displacement of a homogeneous medium along the axis of sound propagation (x component) due to a radiation force applied by a focused transducer operating in an amplitude modulating mode, e.g., $Sin(\Omega t)Sin(\omega_0 t)$ is:

$$S_x = \frac{\alpha a^2 I_0}{2c\rho} e^{-2\alpha x} \int_0^\infty \frac{Exp\left[\frac{-a^2 f^2 \beta^2}{8}\right] J_0(\beta r)\beta}{\sqrt{\left(\beta^2 c_t^2 - \Omega^2\right)^2 + \left(\Omega \beta^2 \nu\right)^2}} Sin\left(\Omega t - \arctan\frac{\Omega\beta^2\nu}{\beta^2 c_t^2 - \Omega^2}\right) d\beta,$$

[0021] where α and c are the attenuation and speed of ultrasound, ρ is the density of the medium I_0 is the intensity of ultrasound at the beam axis, $\nu=\eta/\rho$ is the kinematic shear viscosity, c_t is the shear sound speed (mathematically related to the shear elasticity) of the medium, J_0 is First kind Bessel function of order zero, β is the dummy variable for integration, a is the radius of the transducer (Fig. 1), x is the direction of propagation of sound. These equations can be found, for example, in Ultrasound in Medicine & Biology, 24:1419-1435, 1998, A.P. Sarvazyan, et al., which is incorporated herein by reference for its

description of this equation. The transducer coordinates are shown in Fig. 1, where the radius is a, the direction of propagation x, and the distance to the focus of the transducer is d.

[0022] For harmonic vibration, the velocity is equal to the displacement times the frequency of vibration.

$$V_x = S_x \cdot \Omega.$$

A relationship therefore exists between the vibration of velocity and the shear parameters of the medium in which the wave is produced.

[0023] Referring now to Figs. 2 and 3, graphs illustrating the results of computer simulations of the amplitude of vibration velocity at the focus of the transducer, for a transducer having a radius a=5 cm, a geometric focus d= 8 cm, and a center frequency of 1.5 MHz are shown. Referring first to Fig. 2, a simulation was produced for a homogeneous medium having a fixed shear viscosity of 0.5 Pa*s and a varying shear elasticity of 4, 6.25, and 9kPa for each of the curves 20, 22, and 24, respectively. Under these conditions, each of the velocity curves exhibits a resonant frequency, and the resonant frequency increases as the medium becomes less elastic or more stiff. Referring now to Fig. 3, here the shear elasticity is fixed at 4kPa and the shear viscosity for the curves 26, 28, and 30 is varied, the shear viscosity for the curves being provided at 0.1, 0.5 and 1 Pa*s, respectively. Here, again, each of the curves 26, 28, and 30 exhibits resonance. Here the resonance decreases with increased viscosity. The resonance profile, therefore, is related to the shear viscosity and the shear elasticity, and can be used to determine or estimate these parameters.

Operation

[0024] Referring now to Fig. 4, an apparatus for determining elasticity parameters, particularly a shear viscosity and a shear elasticity of a medium under test is shown. The apparatus comprises a focused ultrasound transducer 10, directed at a medium 14, and a

detector 12, here a laser vibrometer, such as, for example, those disclosed in U.S. Patent Numbers 5,159,416 to Adler or 5,495,767 to Wang, which are hereby incorporated by reference for their description of such devices. The focused ultrasound transducer 10 is directed at the medium 14 to be tested, and the laser vibrometer 12 is positioned to receive a reflected signal for detecting the velocity of vibration at the focal point of the transducer 10 in the medium. As described above, the transducer 10 applies a focused ultrasound wave, preferably an amplitude modulated wave, oscillating at a frequency of less than 5 kHz. The applied wave is a continuous ultrasound wave whose amplitude is modulated sinusoidally.

[0025] Here, the medium 14 is a homogeneous transparent gel including a layer of white paint to provide a reflective surface for laser measurement by the vibrometer 12. The width of the layer of paint is selected to be sufficiently wide to allow reflection, but sufficiently thin such that the effects of the paint can be ignored in the results. The focus of the transducer 10 is focused at the paint layer. The velocity of vibration at the focus of the transducer 10 is detected by the laser vibrometer 12.

[0026] To determine a shear viscosity or shear elasticity of the medium 14 under test, a processing unit or computer device 16 selectively drives the transducer 10 to produce a plurality of ultrasound waves at varying frequencies over a selected frequency range which can be, as shown in Fig. 5, between zero and 8 kHz. As described above, the applied wave is continuous, and has an amplitude which varies sinusoidally. Velocity readings are acquired corresponding to the selected frequency steps. The frequency and velocity coordinates are stored in a memory component 18 as coordinate points in a velocity versus frequency resonance spectrum. The resonance spectra and/or resonant frequency data can be compared against known data stored in a data structure in the memory component 18 to determine the shear properties of the medium under test. For a homogenous medium 14 as described, data can be acquired at a single location in the medium 14. For a non-homogenous material,

spectra data can be gathered for various locations throughout the medium to characterize, for example, variations in a tissue sample. Such a method can be used, for example, to evaluate calcification and to biopsy tissue.

[0027] Referring again to Fig. 5, a chart illustrating the velocity versus frequency spectra for three different homogeneous mediums having gel concentrations of 10%, 15%, and 20% respectively, and therefore having increasing stiffness characteristics are shown. For each of the gel phantoms, the frequency of the applied vibration of the transducer 10 is shown as varied over a range between zero and 8 kHz, along with the corresponding velocity readings acquired by the detector 12. The velocity spectra for each of the gel concentrations show resonance, with the resonant frequency increasing as the medium 14 becomes stiffer (i.e., with a higher concentration of gelatin). As described above, the shear elasticity and viscosity can be determined by comparison of the collected data to a resonance profile or to known resonant frequencies. This method can be used therefore, to estimate the shear properties of the medium.

[0028] Referring now to Fig. 6, the focused ultrasound transducer 10 can also be a confocal transducer comprising two elements 11 and 13 which produce two focused beams 15 and 17 that cross each other at their focal points, as described in U.S. Patent Number 5,991,239 to Fatemi-Boosheri, et al., which is hereby incorporated herein by reference for its description of such devices. The elements 11 and 13 can be driven by continuous wave synthesizers 19 and 21, or by other methods as described in the cited reference, at ultrasound frequencies f_1 and f_2 producing a beat force having a frequency $\Delta f = f_1 - f_2$. As described above with reference to Fig. 4, the transducer can be driven by a processing unit or computer device 16 to drive the confocal transducer to produce ultrasound waves at varying frequencies. While a confocal transducer is shown here, transducers which produce two or

more ultrasound beams with different frequencies can also be applied, irrespective of whether the beams are confocal.

[0029] Although the invention has been described with reference to an analysis in which the medium is a transparent homogeneous gel, the method described can also be applied to opaque mediums and both homogeneous and non-homogeneous media. The detector, although shown as a laser vibrometer suitable for use with a transparent material, can be provided using an ultrasound based motion detector, such as those described in Shukui Zhao, Yi Zheng, Shigao Chen, and James F. Greenleaf, "High Sensitivity Vibration Amplitude Estimation using Pulse Echo Doppler Ultrasound," Proceedings of 2003 IEEE International Ultrasonic Symposium, 1923-1926; Yi Zheng, Shigao Chen, Wei Tan, and James F. Greenleaf, "Kalman Filter Motion Detection for Vibro-acoustography," Proceedings of 2003 IEEE International Ultrasonic Symposium, 1812-1815, which are hereby incorporated by reference for their description of these devices, or a Magnetic Resonance Elastography system, such as that described in U.S. Patent Number 5,592,085, which is incorporated herein by reference for its description of the MRE method. Each of these systems enable the measurement of motion at the focus of the transducer in the medium. Furthermore, although the apparatus is shown using a focused transducer producing an amplitude modulated ultrasound wave, other methods for vibrating the medium.

[0030] It should be understood that the methods and apparatuses described above are only exemplary and do not limit the scope of the invention, and that various modifications could be made by those skilled in the art that would fall under the scope of the invention. To apprise the public of the scope of this invention, the following claims are made: